JOVIAN DECAMETRIC ARC PATTERN AND MULTIPLE REFLECTION ALFVÉN WAVE MODEL

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Abstract

The Voyager Planetary Radio Astronomy Experiment (PRA) revealed prominent arcs when the data were displayed in time–frequency coordinates. These data are consistent with multiple currents flowing along Jovian magnetic flux tubes, each current radiating conically at angles 60° up to 90°. The spacings between adjacent PRA L–burst arcs were analyzed and found to be very brief, about 1–3 minutes, which is much less than the Alfvén wing produced by multiple reflexions of an Alfvénic disturbance. Since the Alfvén pattern is fixed to Io, while a stationary observer primarily sees variations in emission with longitude, we have considered the Voyager (V) emissions during Jupiter V1 and V2 encounters (A or B–sources) occurring at the same observing geometry (observer's longitude and Io phase); it is shown that they are remarkably similar. In a step further, we organized observations of the A and B sources for fixed 30° longitude intervals, with respect to the Io phase and found a clear pattern of regions of strong emission separated by "holes" regions with weak or no emission. This emission pattern may correspond to the pattern of Alfvén wings generated by Io, each Alfvén current causing multiple beams of DAM emission. The duration of the A–source suggests that less than 20% of the Alfvén wave energy is dissipated each time the disturbance travels between hemispheres.

Introduction

Since Bigg (1964) made the discovery that Jovian decametric radio emission (DAM) is modulated by the orbital position of Io, many hypotheses and theories were proposed to account for the interaction between Io and the Jovian magnetosphere. Drell et al. (1965), first expressed the idea that a pair of Alfvén wings forms attached to a conducting body, when the body moves through a magnetized plasma. The Voyager pass by the Io flux tube showed clearly that the Io interaction consists of the generation of large amplitude standing Alfvén waves which propagate northward and southward along the magnetic field lines from Io (Belcher et al., 1981; Acuña et al., 1981; Barnett, 1986). The Voyager Radio Astronomy experiment (PRA) showed that the DAM appears arc–structured in the frequency–time plane (Warwick et al., 1979b). To explain this arc pattern, Gurnett and Goertz (1981) proposed that field–aligned currents are carried by the Alfvén disturbances as they bounce between the northern and southern hemisphere. Multiple reflections could occur because the reflected wave would not be terminated by Io, which would have time to move out of the way before the wave returned from Jupiter: a standing Alfvén wave system would be generated by the motion of Io through the plasma torus (Figure 1).

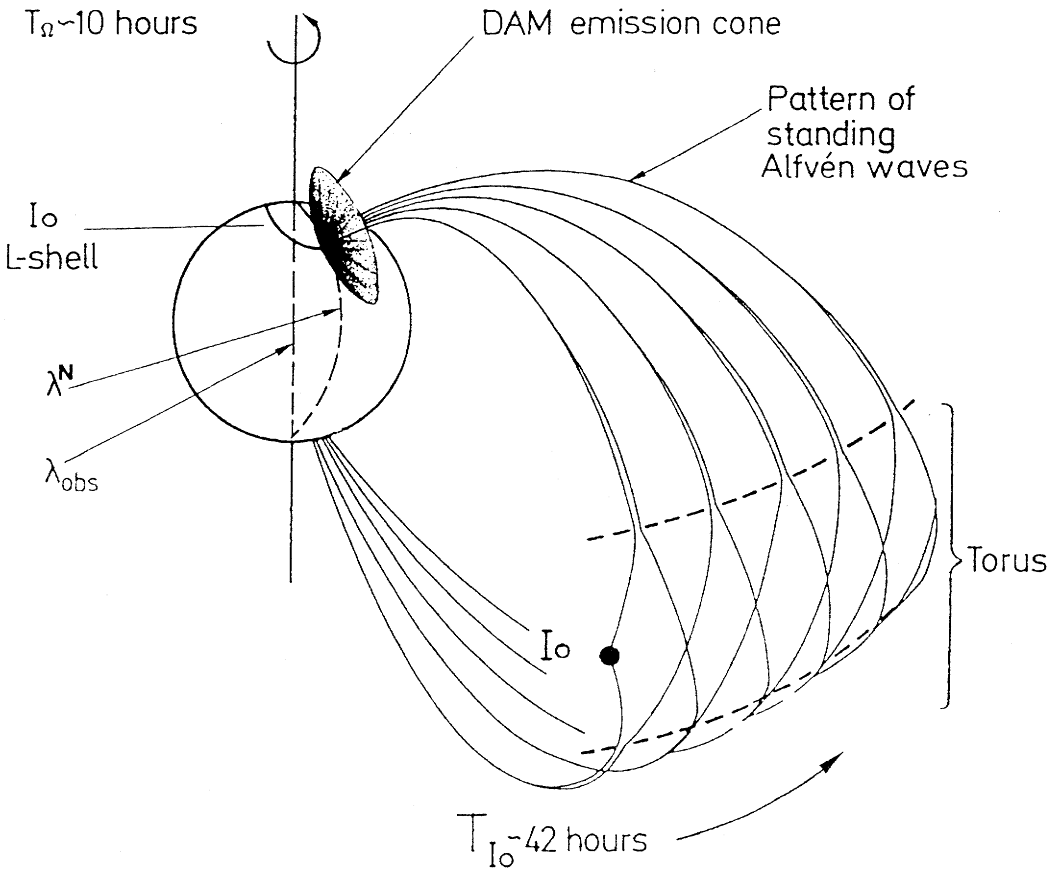

Fig. 1: Geometry of an observer at System III longitude λ_{Obs} with respect to the (A–source) emission region (longitude λ^N) at the northern foot of a field line on the Io L–shell ($L \approx 6$). The emission is believed to be beamed in a thin conical sheet. The pattern of standing Alfvén waves moves with Io completing an orbit in ≈42 hours.

To calculate the time an Alfvén wave would take to travel between Io and the Jovian ionosphere Bagenal (1983, 1985) used the distribution of plasma in the torus derived from Voyager 1 plasma measurements and the 04 magnetic field model. In Figure 2 is presented the round–trip time for an Alfvén wave moving between Jovian hemispheres along a given field line: the variation with longitude is due to the fact that Io is not confined to the magnetic equator and that the magnetic field strength is dependent on longitude. Because Io simultaneously generates both north – and south – moving Alfvén waves, the basic interval between arcs should average ≈ 12 minutes, which is one–half the round trip time.

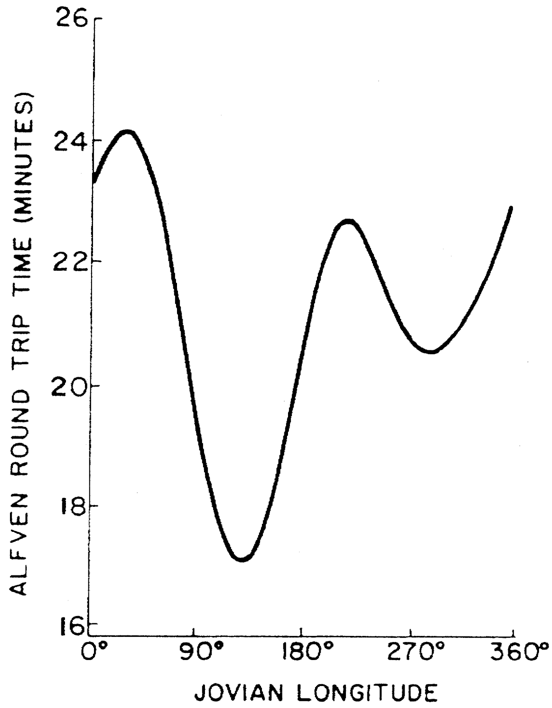

Fig. 2: Predicted round trip–time for magnetospheric Alfvén waves excited by Io, as a function of Jovian longitude.

To test this model we have considered the Voyager 1 and 2 PRA data for L–burst arcs. In the first section is presented the longitudinal distribution of vertex–early and vertex–late arcs, and the distribution of the intervals between consecutive arcs as a function of Jovian longitude. These data are consistent with multiple currents along Jovian magnetic flux tubes, each current radiating conically at angles 60° up to 90°. However, the observed arc spacings are about 2.5 shorter than the predicted ones. The problem is that the Alfvén pattern is fixed to Io with orbital period of 42 hours and therefore varies with the phase of Io, while a stationary observer primarily sees variations in emission with longitude (which has 10 hours period). We confirm in section 2 that for a fixed geometry the emission characteristics are repeated if two emissions (A or B–sources) occur at the same observing geometry (observer's longitude and Io phase). In a further step we organized observations of the A and B sources for fixed 30° longitude intervals, with respect to the Io phase and found a clear pattern of regions of strong emission separated by "holes" regions with weak or no emission. In section 3 we compare the observed pattern of emission and a calculated Alfvén wing pattern generated by Io. The implications of this study are discussed in the conclusion.

1. Observations of L–burst arcs

Catalogues of 100 representative arcs were prepared for Voyager 1 and Voyager 2 emissions, and catalogues of 100 gaps between adjacent arcs were similarly prepared for each spacecraft (Staelin et al., 1988). The principal catalogued parameters discussed here are the time, vertex frequency, Jovian longitude, Io phase, and thickness of each arc at the vertex frequency. Vertex frequency is defined to be that midrange frequency at which an arc first or last appears (Figure 3). Vertex–early and vertex–late arcs are observed

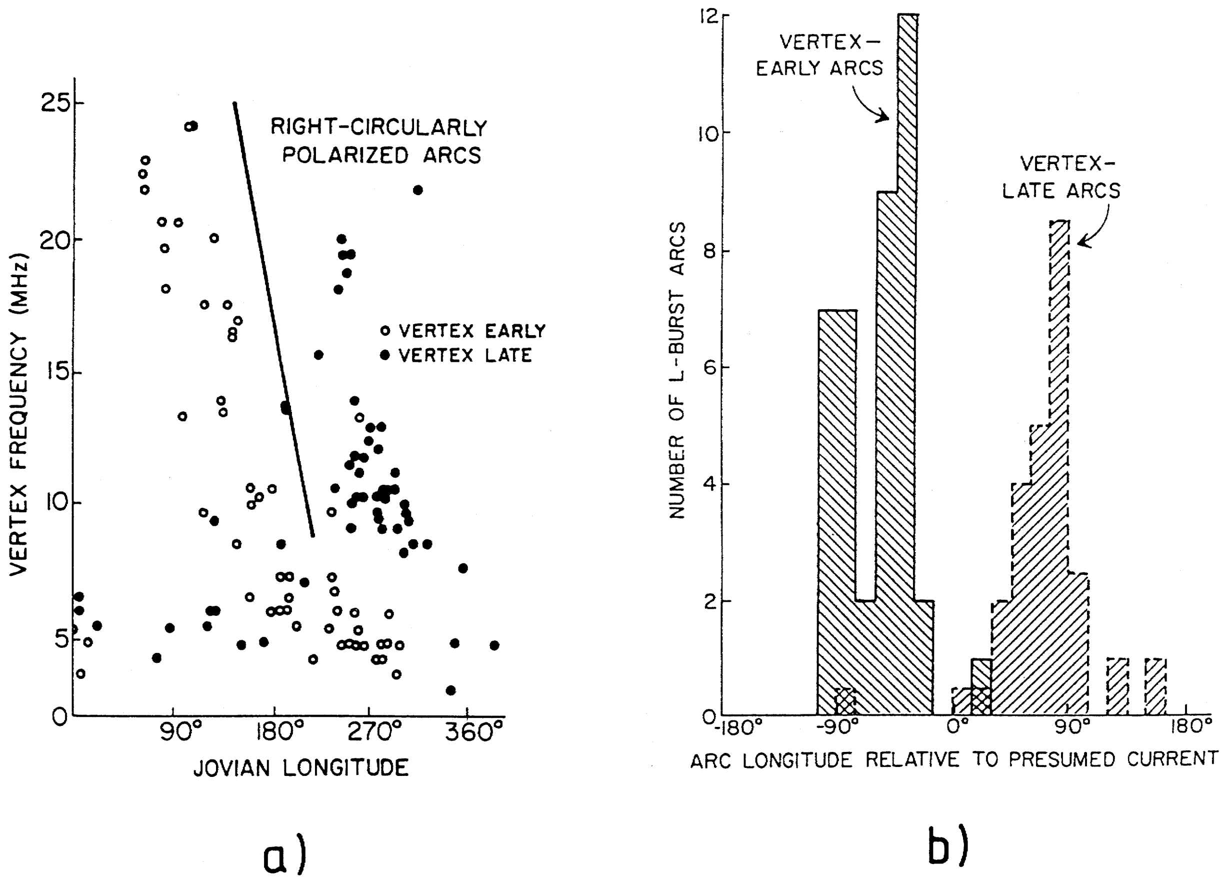

Fig. 3: (a) Distribution of vertex frequency for right circularly polarized arcs as a function of Jovian longitude. The straight line represents the presumed longitude of current radiating arcs at the indicated vertex frequency. (b) Distribution of observed decametric arc longitudes relative to the longitude of the presumed radiating current (After Staelin et al., 1988).

first and last, respectively, at their vertex frequency. The time and coordinates of an arc refer to the middle of the emission observed at the vertex frequency. The Jovian longitude of an arc is the central meridian longitude of the spacecraft at the time of observation. Estimates of vertex frequency and time occurrences are typically accurate to 1–2 MHz and 1–2 minutes, respectively. Arc gaps were estimated with accuracies of 1 minute or less.

1.1 Distribution of vertex–early and vertex–late arcs

Figure 3 shows that most vertex–early and vertex–late arcs are systematically offset in longitude by $\approx 120° - 140°$, consistent with a hollow cone of radio emission aligned with the local magnetospheric field and flared outward at a half angle of $\approx$ 70–90 degrees.

Based on the data in Figure 3a simple equation for the longitude $\mathrm{Lo}(\mathrm{f}_v)$ of the presumed cone axis was fit to the vertex frequency f_v(MHz) for $8 \leq \mathrm{f}_v \leq 25$ MHz;

$$Lo = 256 - 4.56\, f_v\, degree \tag{1}$$

The difference between Jovian arc longitude and cone axis longitude $Lo(f_v)$ was then computed for each arc, and the histogram for the arcs appears in Figure 3b, where vertex–early and vertex–late arcs are plotted separately. The histogram suggests that typical cone half angles projected on the Jovian equator (i.e., perceived by Voyager) are ≈ 50–90 degrees, and that they seldom exceed 90 degrees.

1.2 Arc spacings

In Figure 4 are presented the observed intervals between arc pairs as a function of the presumed Jovian longitude of the radiating current. Typical catalogued arc intervals are only 4–7 min, versus 13–17 min for the predicted initial intervals, a factor of about 2.5 greater.

On the other hand, high resolution data from the Nançay radio observatory (Leblanc, 1981) suggested the DAM arcs are frequently less than 1° apart. Thus there appeared to be a serious discrepancy between the arc spacing predicted by the Gurnett and Goertz (1981) Alfvén wave model and the observations.

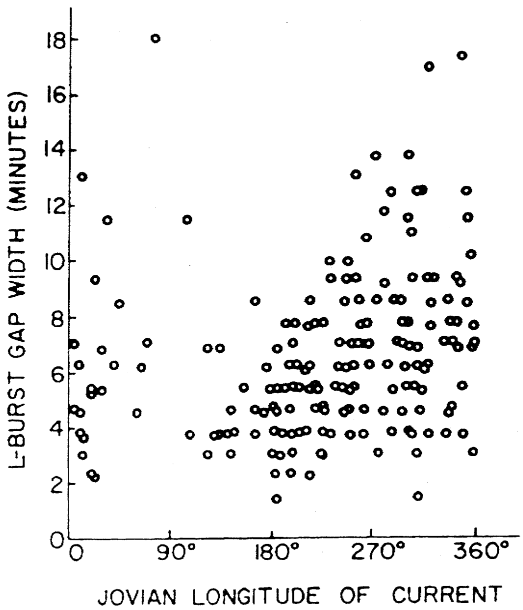

Fig. 4: Distribution of the L–burst arcs spacings, as a function of Jovian longitude of the presumed radiating current (After Staelin et al., 1988).

2. Geometrical conditions of the observations

For a stationary observer, Jupiter's rotation (period ≈ 10 hours) produces rapid changes in viewing geometry due to the highly asymmetric magnetic field. Thus all studies to date have been based on (System III) longitude, λ_{III} (or, equivalently, time) of a stationary observer. The Alfvén pattern, however, is fixed to Io which orbits Jupiter every ≈ 42 hours and hence moves much slower with respect to a stationary observer. We therefore need to take a fixed longitude and consider the variation in emission with respect (Φ) in its orbit. This effect is illustrated in Figure 5. Because of the roughly 4:1 ratio of the periods, a stationary observer makes a gently rising track across the longitude–Io phase

($\lambda - \Phi$) plane (Fig. 5a). In the vertical frequency–time (f–t) plane we have drawn the characteristic vertex–early and vertex–late arcs of the two main (A and B) Io–modulated emissions that would be observed by a stationary observer. Because longitude varies more quickly than Io phase for a stationary observer the f–t spectrograms of both ground–based and Voyager data show mainly longitude variations.

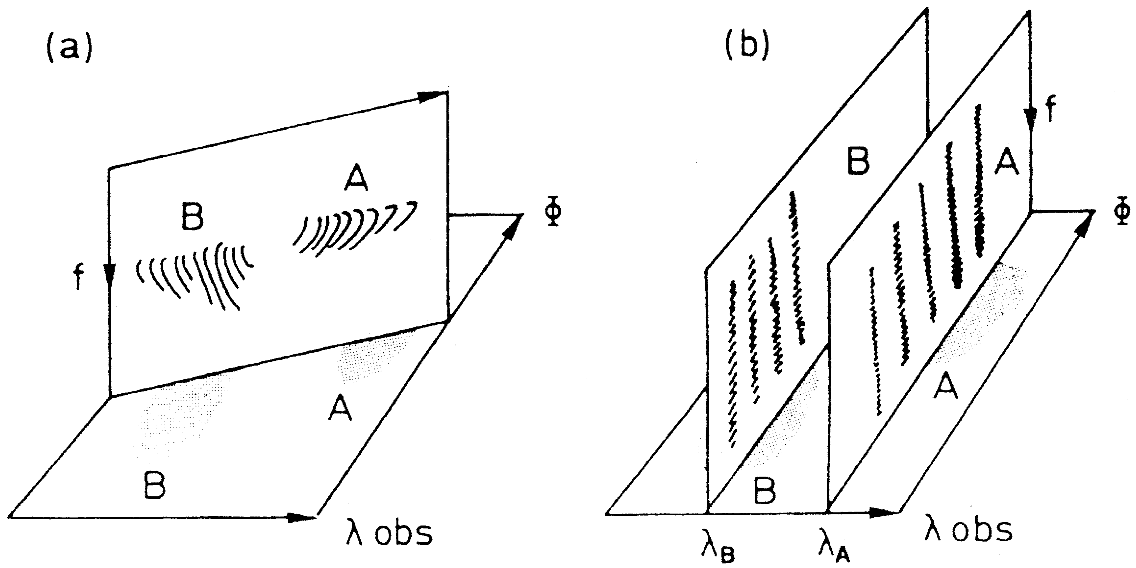

Fig. 5: The main Io–modulated emissions are found in the hatched regions marked A and B in the plane of Io–phase, Φ and System III longitude of the observer, λ_{Obs}, the vertical axis is inverse frequency, f. In (a) the vertical plane is an illustration of a characteristic frequency–time spectrogram for a stationary observer. In (b) the 2 vertical planes illustrate frequency–time spectrograms that would be observed by an observer rotating with Jupiter at fixed longitudes λ_A and λ_B. The vertical bars (increasingly fainter at lower Φ) represent bursts of emission of diminishing intensity.

In Figure 5b we have drawn two cuts of the $\lambda - \Phi$ plane that one would like to make in order to study the variation in emission with Io phase. To do this an observer would have to rotate with Jupiter with a fixed longitude. In this frame Io appears to orbit in the opposite direction, Φ decreasing with time, at an orbital period of 13 hours.

One would then observe, assuming a fixed conical beaming geometry, bursts of emission from the foot of a particular field line as the Alfvén wave pattern slowly moves past. We have sketched broadband bursts but the dynamic spectrum in this frame is probably more complex. If we assume the Alfvén wave to loose some of its energy as it bounces between hemispheres we would expect the bursts of DAM emission to get progressively weaker.

The obvious advantage of this reference frame is that the geometry between the observer and the emission regions is fixed and one need not consider the complicated variation in magnetic field geometry with longitude. To approximate such a reference frame we have taken PRA data obtained by Voyager 1 (V1) and Voyager 2 (V2) at Jupiter for a short longitude interval for each of the A and B sources and organized the data with respect to Io phase.

2.1 Fixed geometry observations

To confirm that for a fixed geometry the emission characteristics are repeated, we first considered occasions where the observer's longitude and Io's phase Φ were duplicated (Figure 6). For each source we found that when the coordinates were exactly the same (to within 1°) the detailed features of the arc structures were remarkably similar. This persistence of spectral structures has been reported by Leblanc (1981) and by Barrow et al. (1982) and suggest they are permanent features of the sources.

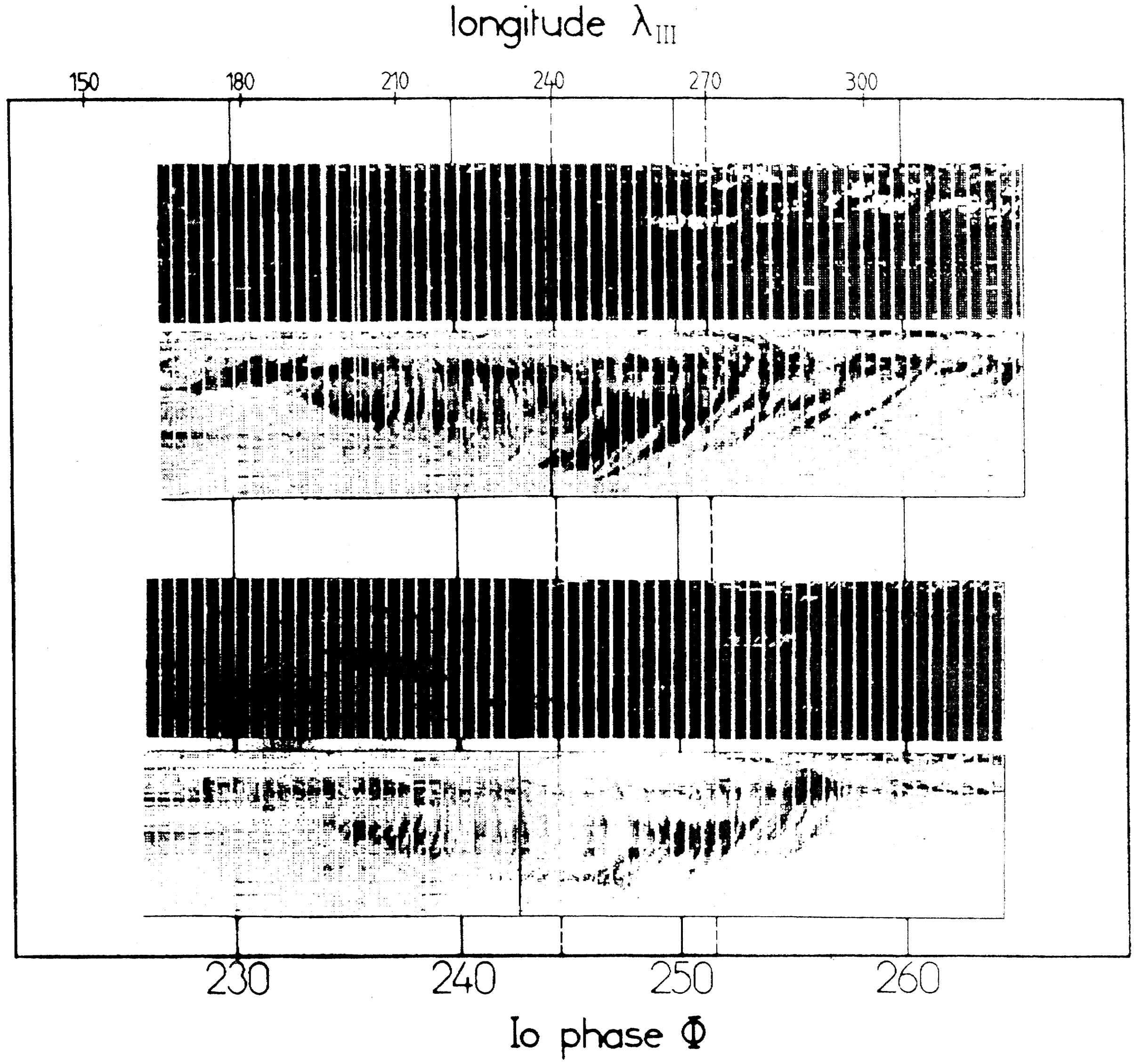

Fig. 6: Dynamic spectra of Jupiter's radio emission observed by the Voyager Planetary Radio Astronomy instrument. The frequency range (vertical axis) is 1.3 to 40 MHz. Two A–source emissions of about 5 hours duration which occurred at the same observing geometry λ_{III}, and Io phase (horizontal axis) are shown (a and b). For each case the upper panel (i) gives the polarization of the emission and the lower panel (ii) shows the total power. Left and right hand polarizations are indicated by black and white shading, respectively. In the lower panel the degree of shading is proportional to emission intensity.

We next considered other occasions where the coordinates were slightly different (by a few degrees) and found that the pattern lined up much better with Φ than with λ_{III}. This suggests that the underlying source pattern is fixed with respect to Io and is repeated with a high degree of accuracy (<1°). Of course it is to be expected that, because the emission geometry is determined by the emission mechanism and magnetic field geometry, the maximum frequency and arc shape will depend on longitude. However this study indicates that certain features of the arc spacing and emission intensity depend fundamentally on Φ and we believe that the longitude effects modulate rather than control emission.

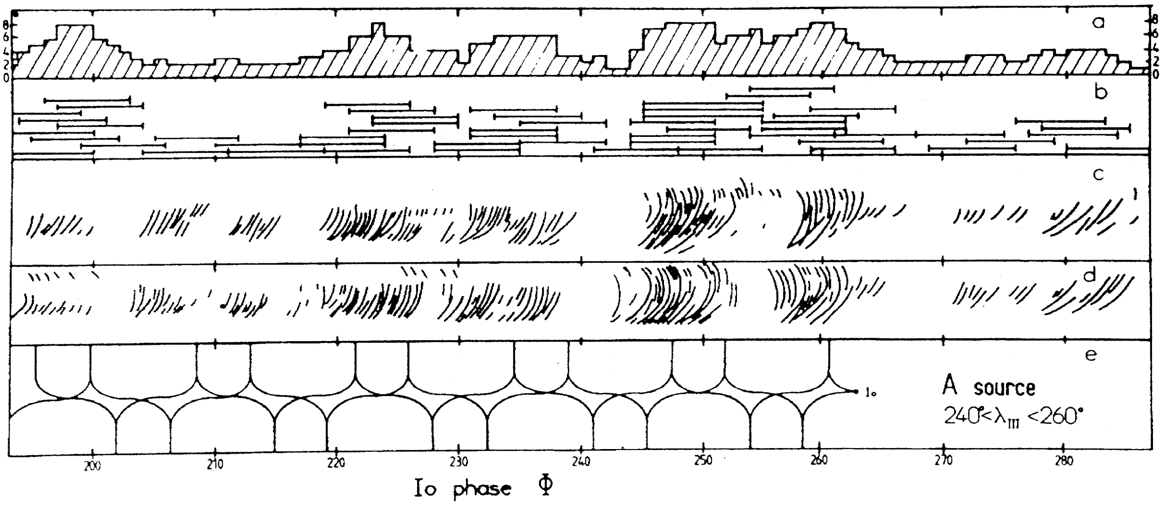

Fig. 7: Arc bunching of A–source emission. The horizontal axis is Io phase Φ. (a) Histogram of number of observations with the given longitude intervals as a function of Φ. (b) Range of Io phase for each observation interval. (c) and (d) traces of arc–features found independently by the two authors in the data sets. (e) The Alfvén wave pattern generated by Io as a function of Io phase Φ for $\lambda^N \approx 166°$.

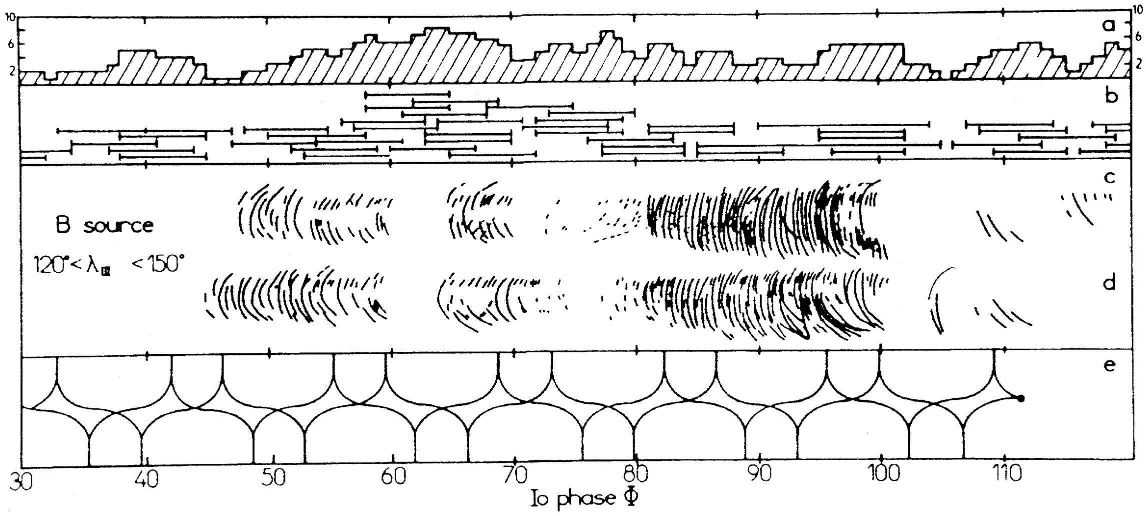

Fig. 8: Same as Figure 7 for the B–source. In (e) the Alfvén wave pattern corresponds to $\lambda^N \approx 201°$.

2.2 Fixed longitude intervals

In a step toward a more quantitative assessment we took all the PRA data for approximatively one month before and after the V1 and V2 Jupiter encounters and considered occasions when $200° < \Phi < 300°$ for the A–source and $50° < \Phi < 150°$ for the B–source. We then took the 30° longitude interval 240° – 270° for the A–source and 120° – 150° for the B–source. We found 55 observations of the A–source region, and 52 observations of the B–source. We have not considered left–hand polarized emissions. For each observation period the main arc features of the emission were traced as a function of Φ. Since the recognition and interpretation of the arc features is somewhat subjective, each of the two authors produced traces of the same data set, independently. Panels (c) and (d) of Figure 7 and 8 show the traces produced by the two authors. In each case the two traces show remarkable similarity indicating the presence of a real pattern in the data. The Φ interval for each observation is shown in panel (b) of Figures 7 and 8. In the corresponding panels (a) above, we have plotted histograms of the number of observations in each 10° interval of Φ. At first glance the spread in the number of observations suggests the gaps in the patterns shown in panels (c) and (d) might just be due to lack of sufficient observations. However closer inspection suggests this is not the case. There are clearly intervals of strong emission with intense and clearly–defined arcs and intervals ($\Delta\Phi \approx 5°$) without emissions. For the A–source, each and every observation in strong emission regions (i.e. near 260°, 250°, 235°) includes intense emissions with the same spectral features, while each of the (albeit fewer) observations in the holes (i.e. near 255°, 240°) shows a complete lack of emission. For the B–source the statistics are rather better, with more coverage of the "holes" (at 75° and 62°). However the B–source dynamic spectra are a little harder to interpret because of the presence of short irregular bursts of emission (shown by dashed lines in the traces) which are the "S–bursts" discussed by Leblanc and Genova (1981).

3. Alfvén wave–pattern

Clearly the individual arcs are too closely spaced to be generated by separate Alfvén wings. However the bunching of arcs into regions of emission and "holes" may correspond to the pattern of Alfvén wings.

To calculate the Alfvén pattern we took the strongest A–source emission (near $\Phi \approx 260°$) to be associated with the Alfvén wing coming straight from Io. Thus for $\Phi = 262°$ and an observer longitude $\lambda_{Obs} = 250°$ then the longitude of Io

$$\lambda_{Io} = \lambda_{Obs} + 180° \tag{2}$$

is $\simeq 168°$. When $\lambda_{Io} = 168°$, the satellite is 7.9° in latitude from the magnetic equator, 5.2° from the centre of the torus (the centrifugal equator). Taking recent models of the plasma in the Io torus (Bagenal, 1985; Bagenal et al., 1985) the complete round trip travel time for an Alfvén wave at L $\approx$ 6 is 23 $\pm$ 1 minutes. From Io's position at 5.2° centrifugal latitude the travel time to the northern ionosphere would be only 4.0

minutes while an Alfvén wave would take 8.0 minutes to reach the southern hemisphere. However the Alfvén wave pattern calculated with these times seemed just a little too closely spaced when compared with the A–source traces. Increasing the time by 18% corresponding to an increase ion mass density of 36%, produced a better match to the spacing of emission and "holes" in the traces about the A–source. The shorter separation between Alfvén wings shown in Figure 7e corresponds to a northern round trip time of $2\times4.0\times1.18 = 9.4$ minutes, and the larger separation corresponds to a southern round trip time of $2\times8.00\times1.18 = 18.9$ minutes. In 9.4 and 18.9 minutes Io moves with respect to an observer at a fixed longitude $9.4\times360/13\times60 = 4.3$ degrees, and $18.9\times360/13\times60 = 8.7$ degrees of Io phase respectively.

With this spacing the Alfvén pattern seems to correspond quite reasonably with the arc pattern if each Alfvén current produces a train of discrete arcs. The holes in the DAM emission line up well with the larger intervals between Alfvén wings, but with our crude analysis technique we are not able to detect a hole or minimum in emission in the smallest spaces in between. It may be that in the smaller intervals the emission arcs from two adjacent Alfvén currents may overlap. On the other hand, the arcs at Io phases greater than 270° are much weaker, seem to have a different arc shape and may not be associated with the Io Alfvén wave pattern.

The Alfvén wave pattern for the B–source was calculated using the same augmented density and travel time but for a longitude of about 200° (Bagenal and Leblanc, 1988): the match between the Alfvén wave pattern and the B–source bursts of DAM emission is quite reasonable except we found no gap in emission at $\Phi \approx 90°$. A proper numerical calculation, integrating emission intensity as a function of Φ (again for a fixed λ interval) is required to investigate the existence of a gap at $\Phi \approx 90°$ as well as in the shorter spaces between Alfvén wings.

4. Discussion

Figure 7 indicates the A–source emission (and hence we presume, the Alfvén wave pattern) extends for at least 70° of Io phase. One would expect that each time the Alfvénic disturbance traverses the torus and is reflected at the ionosphere it looses energy. Estimates of the reflection coefficient at the ionosphere depend on the electrical conductivity of the Jovian ionosphere which is not known to better than an order of magnitude. Gurnett and Goertz (1981) took value 0.1 mho for the integrated Pedersen conductivity and estimated the wave would survive 9 reflections. A more serious problem is the possibility of reflection of Alfvén wave energy at about 10–20° in latitude from the centrifugal equator where there is a steep gradient in plasma density and hence also in Alfvén speed. Wright (1987) estimated as much as 80% of the Alfvén wave energy could be reflected in the torus, depending on the pulse length and shape as well as the density gradient. However, Figure 7 suggests the DAM emission cover over 70° of Io phase which implies that the Alfvén waves last for at least 10 bounces. If we assume the wave does not diminish by more than an order of magnitude over 70° of Io phase then the transmission coefficient per bounce must be greater than 80% . Of course the relationship between the Alfvén wave energy and the DAM emission intensity could be highly non–linear and very weak Alfvén waves may be able to trigger intense emissions.

An important implication of Figure 7 is that each Alfvén current must be triggering several emissions. Indeed inspection of the high time–resolution data from the Nançay observatory suggests there could be 30 arcs in the time interval of 33 minutes corresponding to the $\approx 20°$ longitude or $\approx 5°$ of Io phase of an emission burst associated with an Alfvén current. We propose three possible explanations for these multiple DAM arcs: (i) it is purely a longitude effect which may disappear if we were to consider a longitude interval of less than $1°$; (ii) the Alfvén wing may be split into multiple discrete pulses as it suffers multiple reflections along its path through the torus; (iii) each Alfvén wave triggers several beams of emission with slightly different cone angles. The first possibility can be checked with further analysis of the data. Since the steepest density gradient is a travel time of ≈ 2 minutes from the ionosphere, multiple reflections between the ionosphere and the torus boundary would produce arc spacings of $\approx 2°$ in Φ, at least 5 times farther apart than observed. Moreover, the torus boundary is fuzzy rather than sharp and one would expect the Alfvénic disturbance to spread out continuously rather than be split into discrete pulses. Thus we believe it is more likely that each Alfvén current triggers several beams of emission, rather than the multiple arcs being a result of multiple reflections.

Finally, it must be emphasized that this is only a preliminary study and further, more quantitative work must be done to prove that the emission is associated with the Alfvén wave pattern. In particular, we have not really taken into account the emission intensity which varies considerably within each "storm". A numerical calculation of average intensity as a function of Io phase and frequency for small longitude intervals (i.e. construction of the f–Φ spectrograms of Figure 5b) for several fixed longitudes would be an important test of the model and provide more accurate estimates of the emission geometry and properties of the Alfvén wave pattern (travel times, degree of dissipation and dispersion).

5. Conclusion

- This preliminary study of DAM arc spacing in Io phase, at fixed longitude, suggests that the A and B Io–modulated emission consists of a series of bursts of emission corresponding to the pattern of Alfvén wings generated by Io.
- Each burst of emission comprises several discrete arcs which implies each Alfvén current causes multiple beams of DAM emission.
- The A–source emission pattern lasts for at least $70°$ of Io phase. This suggests that (unless the coupling between the Alfvén and electromagnetic waves are highly non–linear) less than 20% of the Alfvén wave energy is dissipated per bounce.
- This preliminary study provides only an indication of the presence of the Alfvén wave pattern, and further numerical studies of emission intensity as a function of Io phase for several, smaller intervals of fixed longitude are required to provide a rigorous proof and to determine model parameters.